SINGLE-APERTURE FAR-INFRARED SPACE TELESCOPES

CONCEPTS for MAJOR FIR SPACE MISSIONS + MORE

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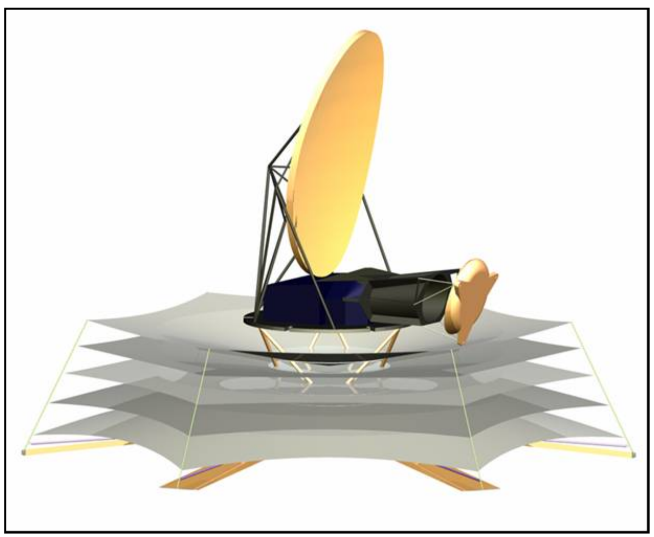
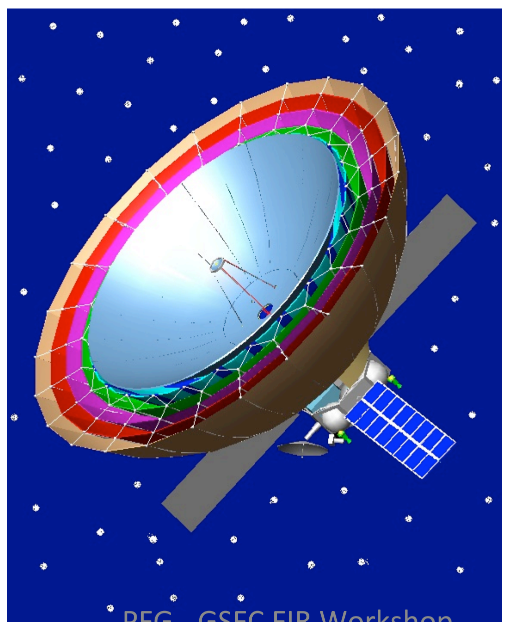
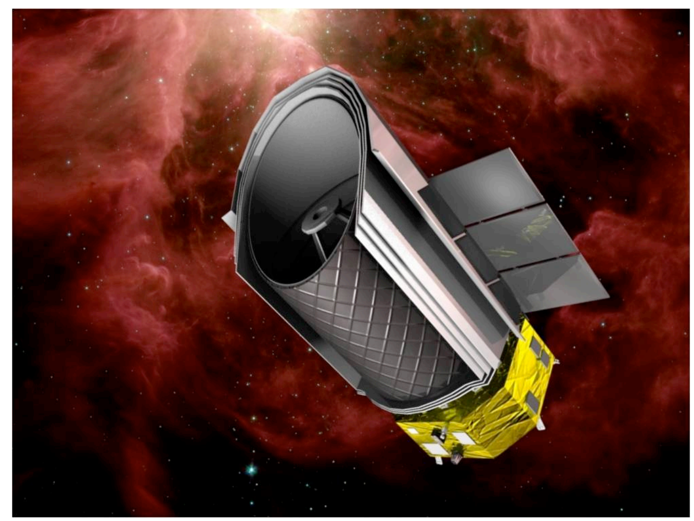






The Basic Question:

What is the justification for a major far-infrared space mission?

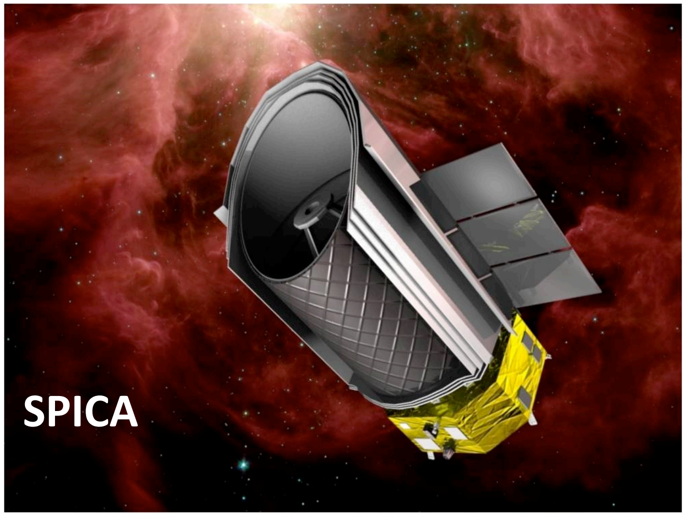
An Answer

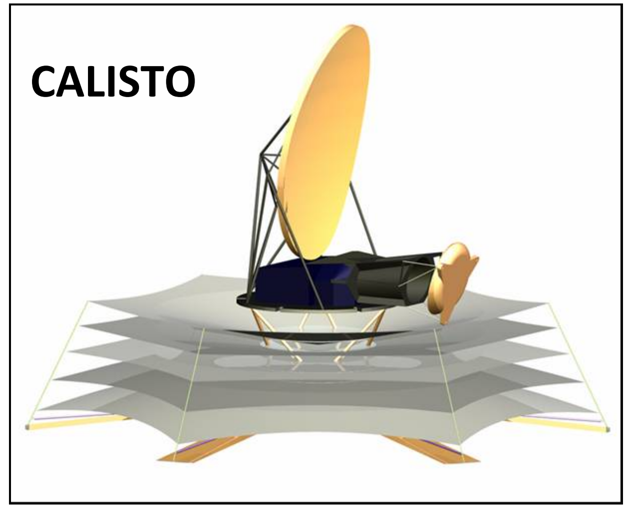
Address a significant scientific question that can *only* be answered with data from an instrument in space

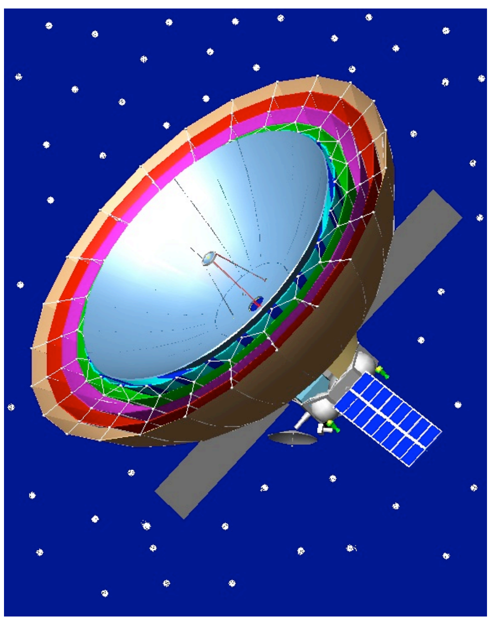
This might include

- Observing at a frequency that is blocked by the atmosphere
- Carrying out a survey that can only be done from space
- Utilizing unique capability of location of space observing platform

Three Concepts for Single-Aperture Far-Infrared Space Missions are Being Actively Considered (but there may be others)







MILLIMETRON (MMSO)

Before discussing mission specific capabilities, it is important to put these MAJOR single-aperture mission concepts in context

There have been:

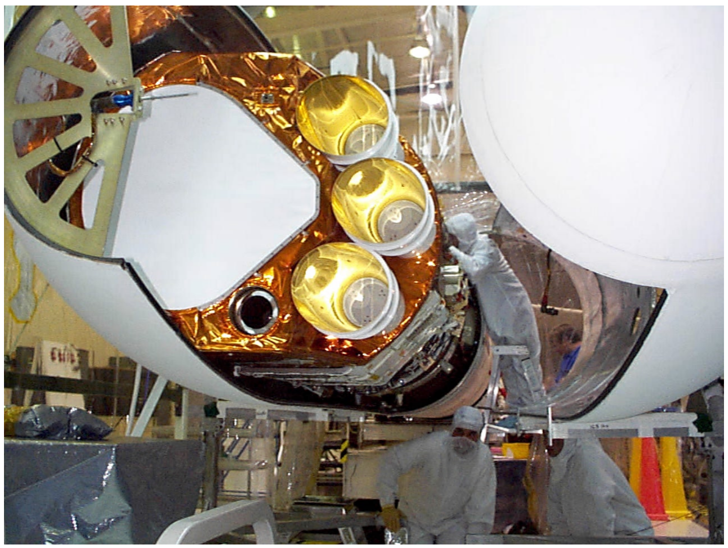
Small Satellites (SWAS, Odin)

Large Satellites (Spitzer, Planck, Herschel)

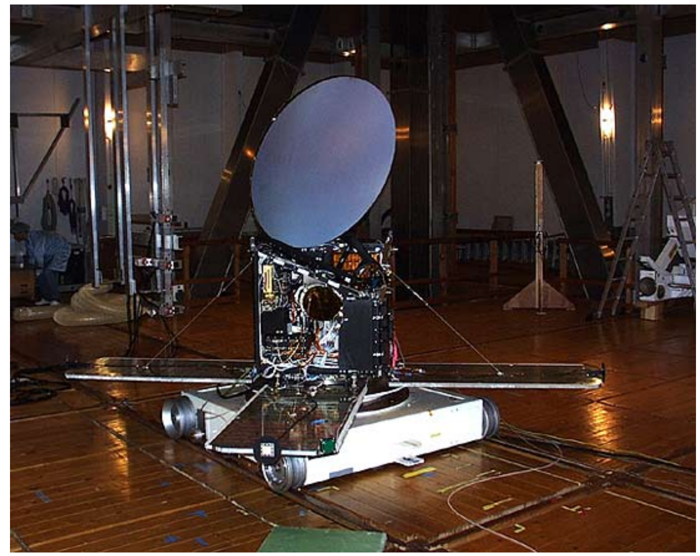
Suborbital Platforms - **Airplanes** (KAO, SOFIA)

-**Balloons** (PIROG, PRONAOS, STO)

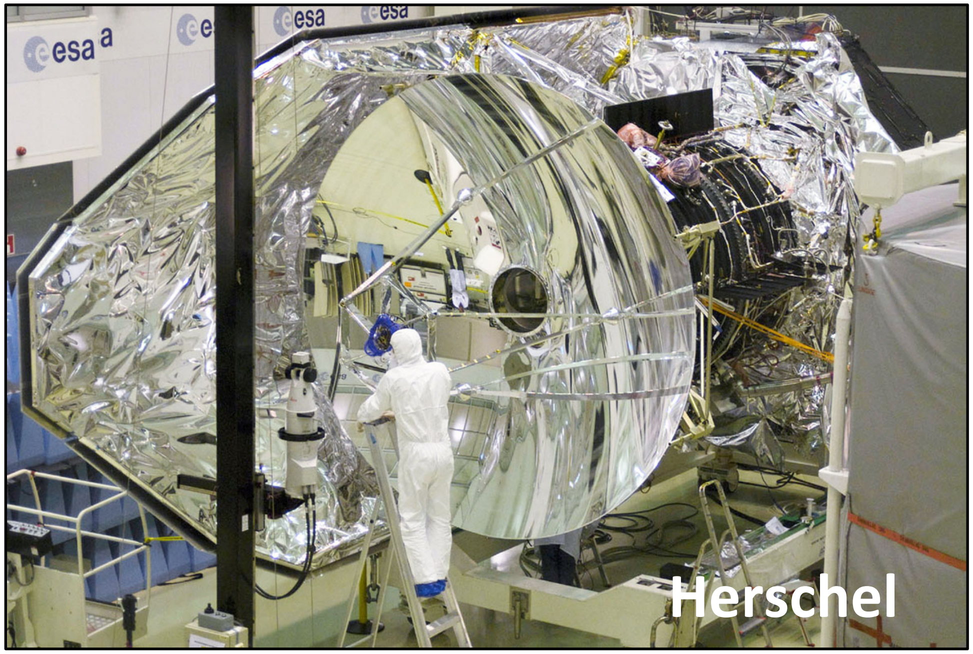
Small Satellites for Far-Infrared (Spectroscopy)



SWAS

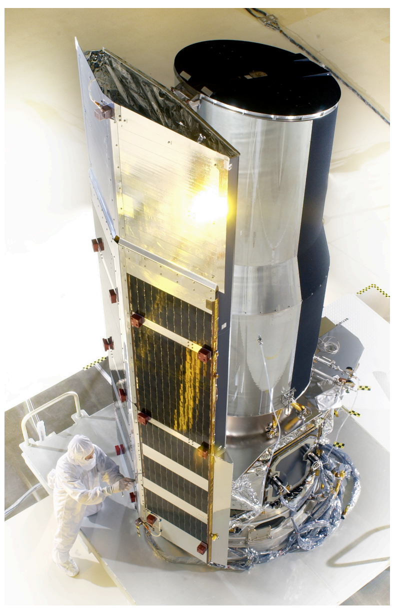


Odin



Observatories with Major Impact on FIR Astronomy

Spitzer



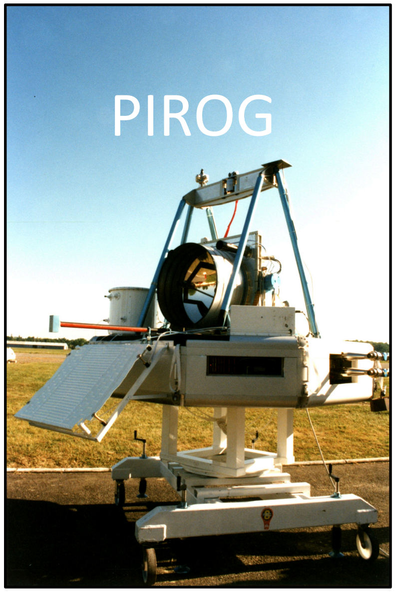
Planck

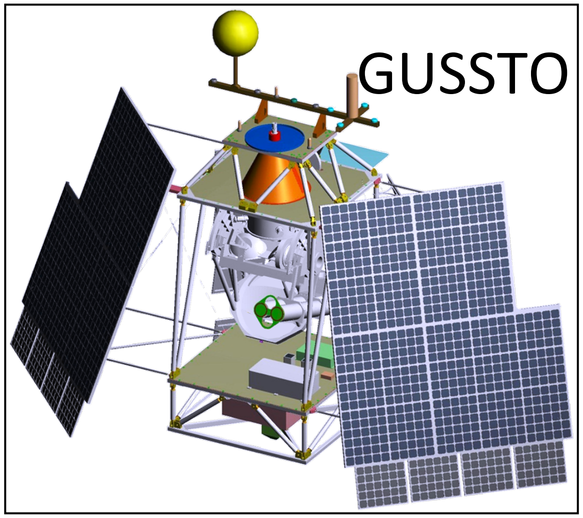
Airborne FIR Facilities

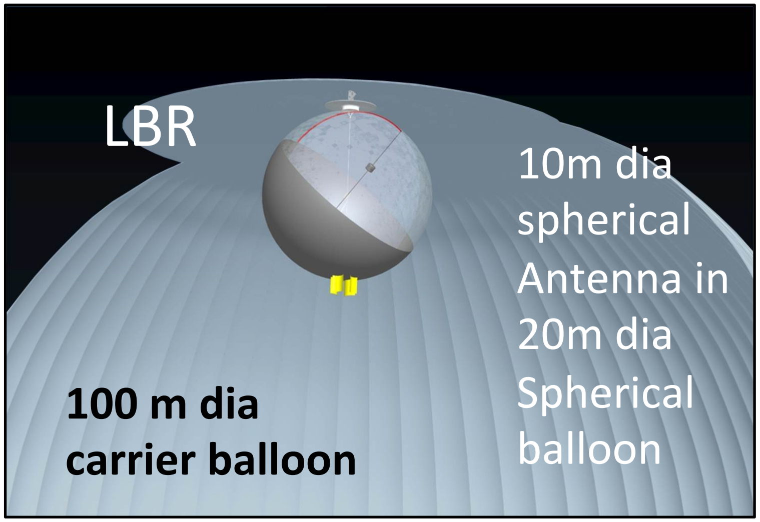
Kuiper Airborne Observatory (KAO)
91.5cm telescope
1974-1995

Stratospheric Observatory for
Infrared Astronomy (SOFIA)
NASA/DLR
2.5m telescope
2010 - ?

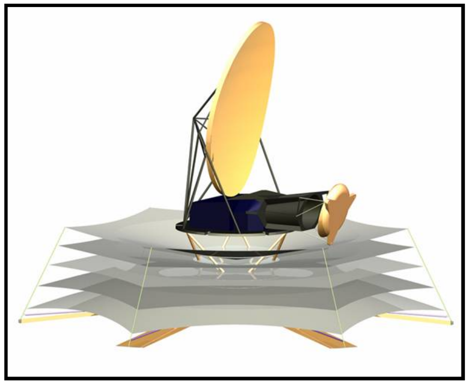
Past and Future FIR Balloon Missions





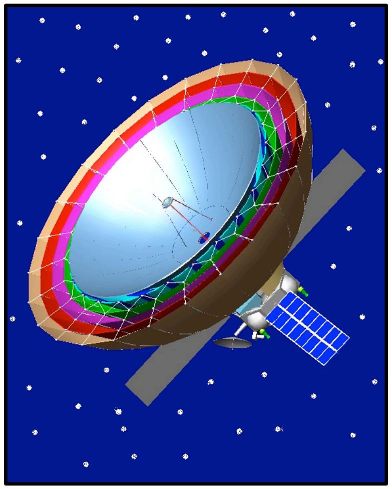


Three Concepts for Single-Aperture Far-Infrared Space Missions



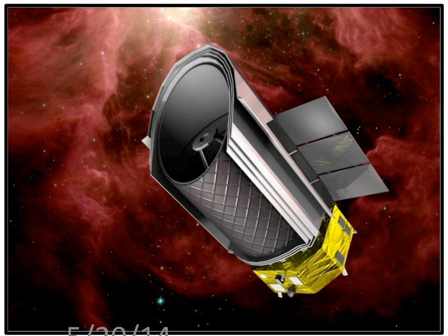
CALISTO

NASA concept deriving from 2005 SAFIR study; to be presented to 2010 Decadal Review. Launch TBD



MILLIMETRON (MMSO)

Astro-Space Center of Lebedev Physical Institute (Moscow) with involvement of SRON and Italy (Space Agency & Univ. Sapienza, Rome). Launch 2019+



SPICA

JAXA Mission with major ESA involvement (telescope; SAFARI instrument). New start in 2014 being proposed in Japan with European M-4 proposal. Launch 2025

My Take: It is Striking that the 3 Major Space Mission Concepts Largely Share Science Goals and Instrumentation, but each has "Individual Features"

Common Features

- Wavelength range 20/50 μm – 300/600 μm
- Cameras, low/medium resolution spectrometers
- Telescope optics cooled to ≤ 6 K (low background)
- Cyrocoolers (no cryogens)
- Long lifetimes at L2

Individual Features

- High resolution multipixel (heterodyne) spectrometer (MMSO, CALISTO?)
- Earth-Space VLBI (MMSO)
- Optimized instrument for S-Z Effect (MMSO)
- Near-IR capability and coronagraph for NIR expolanet research (SPICA)
- Unblocked, cold-baffled aperture to achieve astronomical background limited sensitivity (CALISTO)

Overview of Major FIR Space Missions

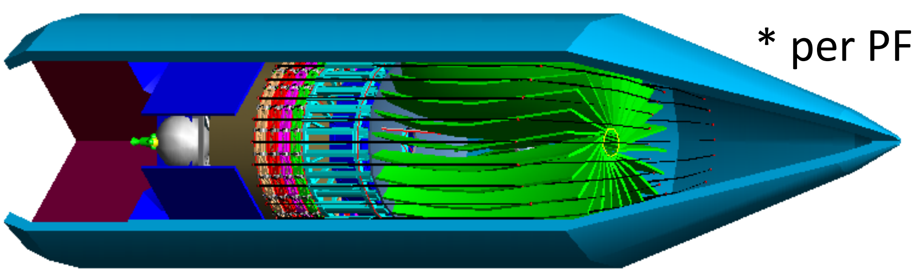
Comparison is complicated by the very different history and current status of each mission

Some key parameters are evolving significantly while others are only partially defined

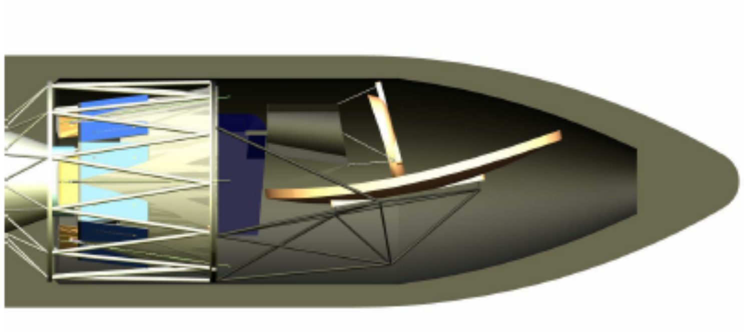
MISSION	Telescope Size	Telescope Type	Surface Accuracy	Wavelength Range	Telescope Temperature
CALISTO	4m x 6m	Off-axis cold-baffled Gregorian		300 µm – 30 µm	< 5 K
MMSO	10m	On-axis fast Cassegrain	5 µm rms	800 µm – 50 µm	4.5 K
SPICA	3.2m	On-axis slow Cassegrain		210 µm – 20 µm	< 6 K

Mission Telescope Comparison

Mission	Telescope Effective Area	Relative Eff. Area at 160 µm*	Telescope Deployment	Risk*	Background*	Confusion Limit
CALISTO	6π * ε(high)	3	Secondary arm pivots ~ 90º	Moderate	Low	Lower 5σ 8 beams = **5 µJy** @ 70µm
MMSO	25π * ε(low)	8	Primary unfurls	High	Moderate	Very Low
SPICA	2.6π * ε(medium)	1	None	Low	Moderate	Moderate



* per PFG



MMSO Furled for Launch

CALISTO Stowed for Launch

CALISTO INSTRUMENTATION

- **CAMERA: 4 sub bands covering 30 μm to 251 μm**
  - 4096 pixels each

- **MED-RES SPECTROMETER: 4 sub bands**
  - **grating or WaFIRS technique with 4 spectrometers per sub band**

Wavelength	Resolution	N_{pix}	Slit (“)
30 – 51	2000	12,000	1.4
51 – 87	2000	12,000	2.3
87 – 147	2000	12,000	4.0
147 – 251	1500	9,000	6.7

(Also considering having many more spatial pixels with lower resolution; ~ same total # of detectors;; M. Bradford’s talk)

- **HIGH-RES (Heterodyne) SPECTROMETER**
  - Focus on key transitions of H_2O and fine structure lines of C+, N+, OI with 16-pixel arrays
  - 557 GHz, 1126 GHz, 1460 GHz, 2000 GHz, 4700 GHz with ±10% tunability

MMSO INSTRUMENATION

- Short-wave Array Camera Spectrometer (SACS)
  - 4 camera bands: 70, 125, 230, 372 μm
  - long-slit grating spectrometers 50 – 450 μm; R = 500-1000
- Long-wave Array Camera Spectrometer (LACS)
  - 4-band FTS optimized for S-Z observations R ~ 500

λ-range(μm)	3000-1500	1500-850	840-450	450-300
FWHM (“)	42	22	12	7.5
# pixels	6	9	25	36

- Millimetron Heterodyne Instrument for the Far-IR (MHIFI)

  550- 650 GHz (3 pixels) 950-2100 GHz (7 pixels)

  2450-3000 GHz (7 pixels) 4760-5360 GHz (7 pixels)
- Space VLBI; single pixel dual polarization HEMT/MMIC & SIS
  - 18-26; 33-50; 84-116; 211-275; 275-355; 602-720 GHz

SPICA INSTRUMENTATION

- SPICA Focal Plane Camera (FPC)
  camera and low-resolution spectrometer, also for guidance
  - 0.7-5.2 μm (5 filters) 5' x 5' FOV 1k x 1k InSb array
  - R = 5 to 20 spectroscopy
- SPICA Mid-infrared Instrument (SMI)
  1k x 1k Sb-doped Si arrays
  - low resolution (R=20) wide-field (5'x 5') spectro-imager [grism]
  - medium-resolution (R=1000) long-slit (2') spectrometer [grating]
  - high resolution spectrometer (R = 20,000) [immersion grating]
- SPICA/SAFARI
  3-band FTS covering 34 -210 μm R = 50 to R = 2000
  - Band centers 47 μm 85 μm 160 μm
  - Ang. Res. 4" 7" 13"
  - Pixels 43x43 34x34 18x18

Astronomical Background Limited Observations

Consider a single mode system coupled to a photon field, which includes contributions from telescope, atmosphere, and the astronomical background

The fluctuations from each contributing source add in quadrature to the fluctuations from the detector

For a space mission, we have no atmosphere, so we are left with detector, telescope, and background

Background contributions are from CMB and dust in in Galactic plane & in the plane of solar system (zodi)

Telescope and background produce fluctuations each characterized by a noise equivalent power (see Zmuidzinas 2003 for full disclosure) = signal detected with SNR = 1 in 1 second integration time

NEP = $h\nu[n(n+1)]^{0.5}[\delta\nu]^{0.5}$ (W/√Hz)

where n = <photon occupancy> = $\varepsilon[\exp(h\nu/kT)-1]^{-1}$ for a thermal source of emissivity ε at temperature T

Note: in R-J limit, $h\nu/kT \ll 1$ so $n \gg 1$ and NEP = $\varepsilon kT[\delta\nu]^{0.5}$

coherent system considered to be blackbody with "input noise temperature" T

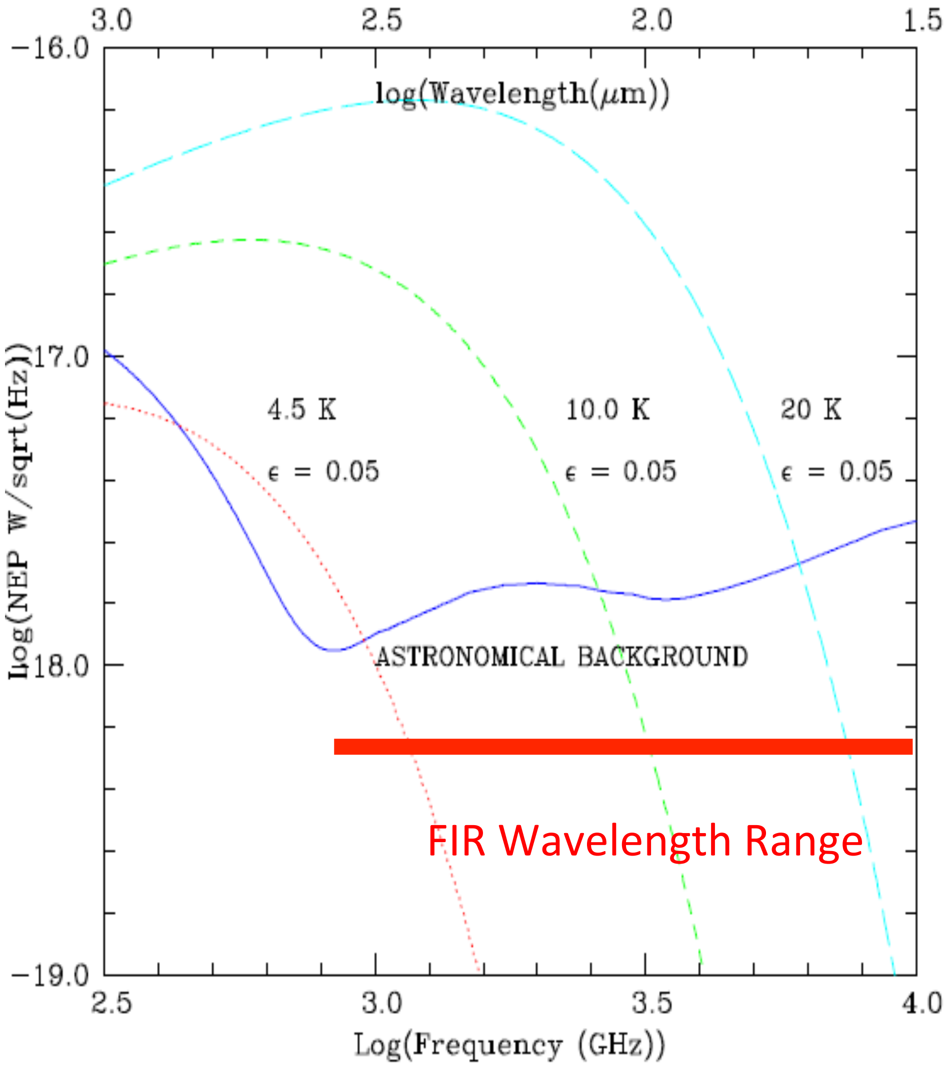
in optical limit $n \ll 1$ so NEP = $h\nu\,[n\delta\nu]^{0.5} = [h\nu\,]^{0.5}$ (power collected)$^{0.5}$

FIRST REQUIREMENT: cool optical system to reduce contribution to NEP below that from the background

Astronomical background at North Ecliptic Pole (minimum)

Noise Equivalent Power (NEP) in $\delta\nu/\nu = 1$ fractional bandwidth

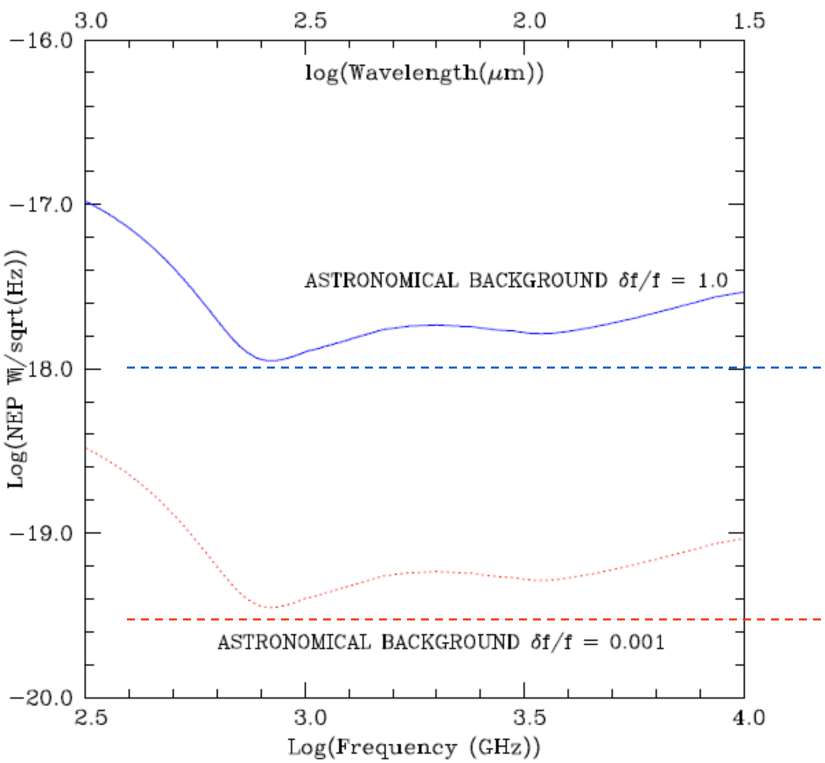
T < 4.5 K ε = 0.05 (total) optics required to have astronomical background determine system NEP for λ ≤ 300 µm



Astronomical Background Limited Observations

SECOND REQUIREMENT: Reduce detector NEP to less than astronomical background NEP (or at least get close)

This is difficult for broadband detectors and very challenging for spectrometers ($\delta\nu/\nu = 0.001$) since NEP varies as $\delta\nu^{0.5}$



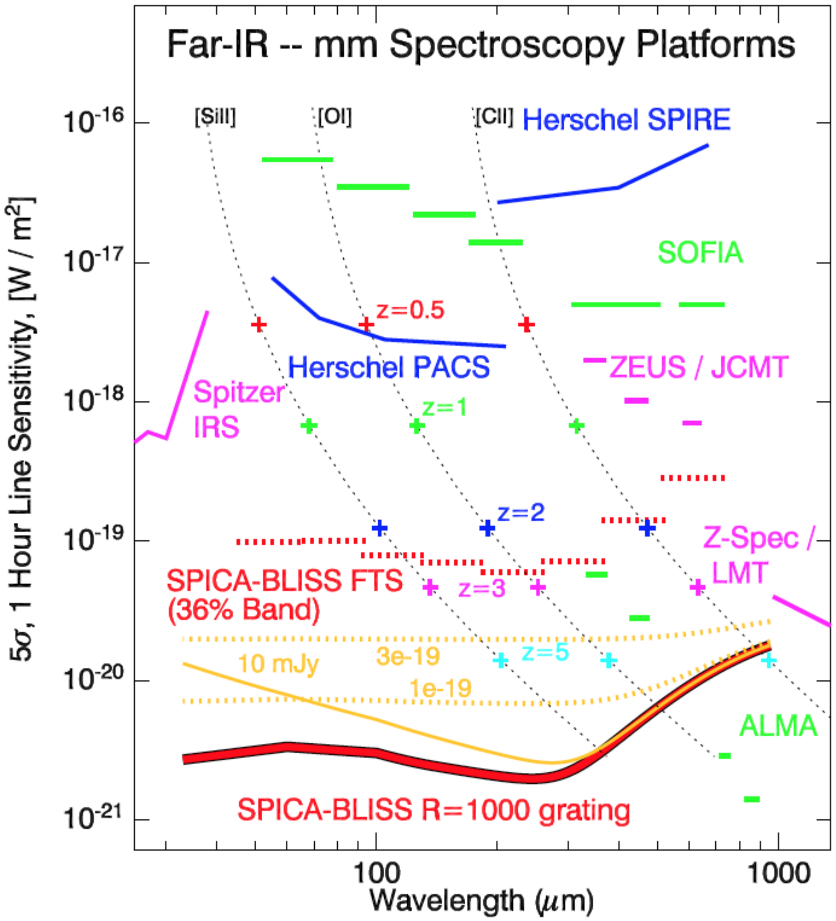
Astronomical background NEP levels for different fractional bandwidths

1×10^{-18} W/√Hz

3×10^{-20} W/√Hz

These are somewhere between difficult and extremely difficult to achieve , especially with modest/ large number of pixels desired

With sufficiently low noise detectors and a cold telescope you are in great shape for photometry and low/med resolution spectroscopy



From Bradford SPIE 2006

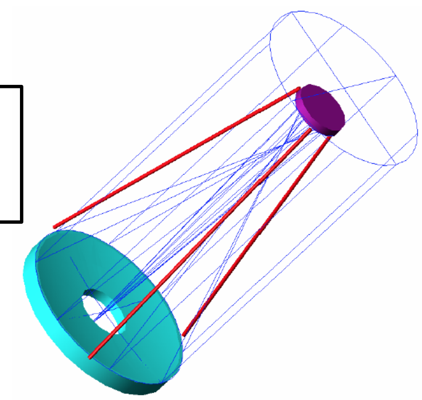
Every major FIR mission presentation has a figure like this one!

CAVEAT EMPTOR!!

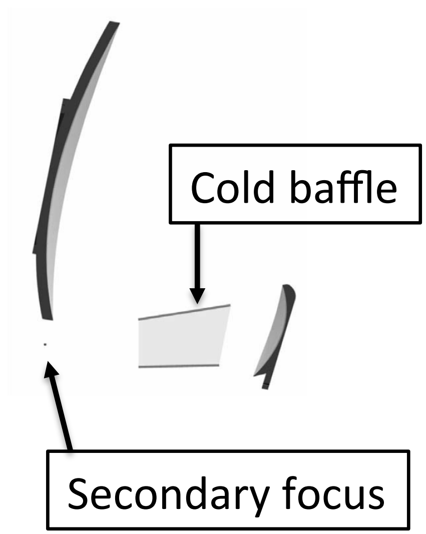
Generally assume cold telescope with negligible emission
“Goal” sensitivity or noiseless detectors
Minimum (or no) astronomical background

Achieving Astronomical Background Limit Operation – Impact on Telescope Design

Typical symmetric telescope SAFIR geometry

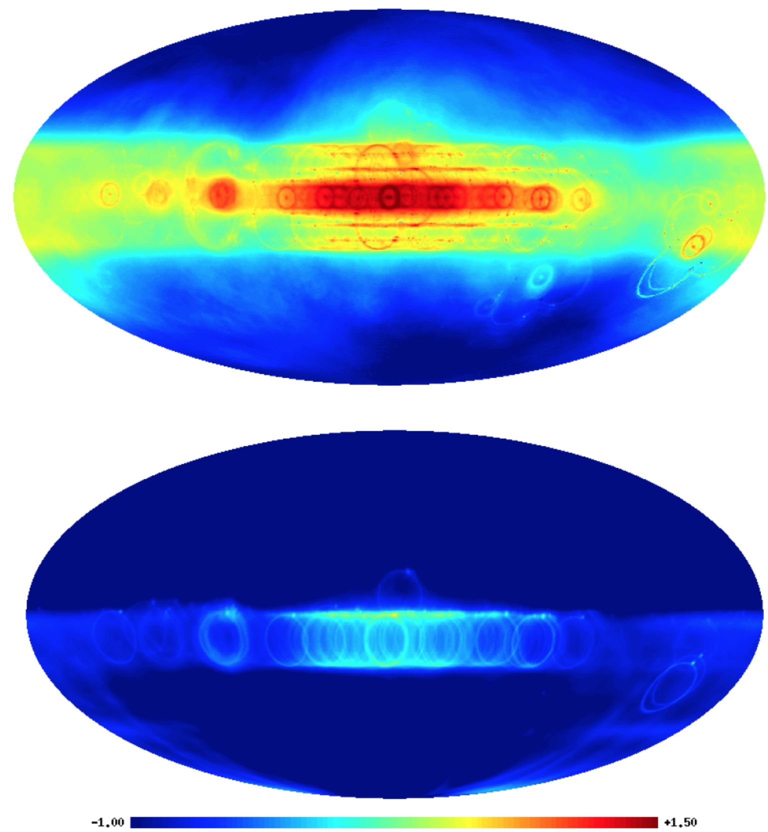


Unblocked (off axis) CALISTO design with cold baffle at image of primary



Limiting NEP α [power collected]$^{0.5}$

Dramatic reduction of pickup from Galactic plane **– most of the sky is DARK**



Log(I_{100}µm/MJysr^{-1})

- In thinking about different missions – consider "transformational" or "killer ap" science that they could accomplish
- Mission capabilities are more similar than distinct, but as presented to date, each does have unique capabilities
- The present workshop may not encompass all areas on which FIR missions may have an impact – e.g. black hole/event horizon physics
- We need to be broad but make sure we have a truly compelling science case
- Keep synergy with other major facilities in mind – notably JWST and ALMA

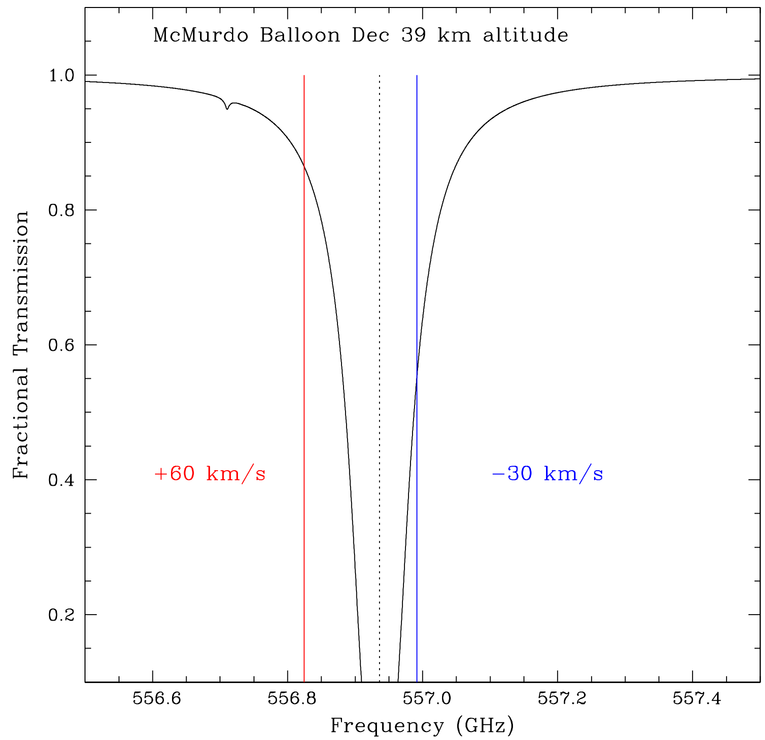
In upcoming science talks, beyond the science, we should also consider the implications for mission requirements in terms **of angular resolution, confusion, spectral resolution, sensitivity**, **and total integration time**

Almost all projects, whether early stars and galaxies, intergalactic hydrogen, distant star formation, protostellar disks, TNOs, and water in the solar system, are sensitivity-limited, but this is not the only important parameter.

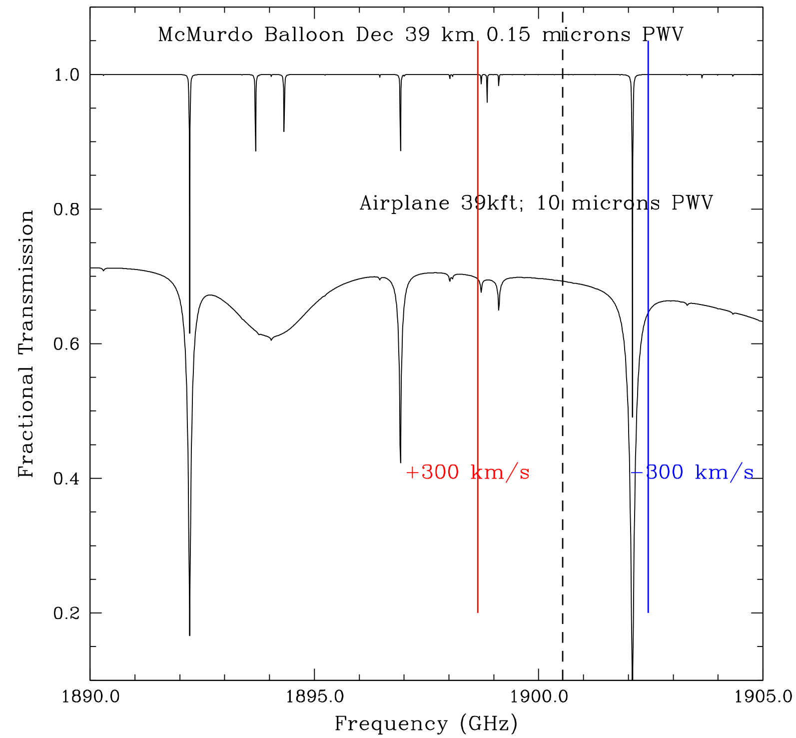
What is the unique contribution of a major FIR mission? Let's focus on that and see how proposed major missions do (or do not) enable it.

Where do Balloons Fit In?

Antarctic balloon is marginal for H_2O
Especially in the solar system



Balloon offers far better transmission for CII and essentially unobstructed velocity coverage



Balloons

- Long duration and now ultra long duration balloons (ULDB) can provide missions of up to 100 days at altitudes of 39 km
- Impressive new capabilities for astronomy but with caveat that telescope will **not** be cooled far below room temperature
- Highly competitive for long wavelengths (RJL) and spectroscopy (other than H_2O and a few other "blocked" frequencies)

CONSIDER ALONG WITH MAJOR FIR SPACE MISSION:

A balloon "facility" with 3-10 m diameter telescope available for use with community-developed instruments. "Major Space Mission" sensitivity for some astronomy +

- Reduced redundancy in developing pointing, housekeeping, and telemetry facilities
- Support science and instrumentation development
- Train astronomers and instrumentalists
- Provide test bed for new instrumentation
- Bring state-of-the art capability to community for fraction of space-mission cost

Bradford; Walker posters

Suggested Activities for the FIR Community in the Near Future

- Support continued development of FIR science based on ongoing analyses of data from Herschel, Planck and suborbital missions
- Develop FIR mission concepts in accordance with addressing key aspects of science case
- Support technology development to enable progress in the future
- Support NASA funding of FIR astronomyand development of Decadal Review concepts
- Advocate development of enhanced balloon platform and opportunities for FIR observations